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An Analytical Approach to the Impact of Heat Waves on Buildings and their Occupants

Alfonso Ramallo-González, PhD

Member ASHRAE

Matthew Eames, PhD

Manuel Herrera, PhD

David Coley, PhD

ABSTRACT

Extreme weather events are expected to become more intense and more frequent, and lead to increases in heat-related mortality. Unfortunately, there is no set of agreed heat wave time series to test new buildings or complete building stocks against. In this work, we attempt to solve this by finding analytical relationships between heat waves and increases in internal temperature for 25 monitored dwellings. The result is a methodology that allows the forecasting of the effect of extreme events on buildings with almost no computational effort. Extrapolating the results to the whole UK domestic stock indicates that, for example, a heat wave of three days with a maximum amplitude of 5 kelvin above the situation prior to the heat wave will result on an increment in internal temperature of 1.5 kelvin or more for 43.3% of dwellings and a rise of 2 kelvin or more in 3.5% of the dwellings by the third day of the heat wave.

INTRODUCTION

An open question is the way in which our buildings will respond to a changing climate. Almost all work on the topic has looked at how climate change will alter typical conditions by applying future representations of typical weather to computer models of buildings (Jentsch, Bahaj et al. 2008, Guan 2009, Eames, Kershaw et al. 2011, Kershaw, Eames et al. 2011). Although useful in looking at annual energy consumption and thermal comfort, when it comes to issues of morbidity and mortality, it is the situation far from typical that is of critical interest, for example heat waves and cold snaps. As the European heat wave of 2003—when over 14,000 died in Paris alone (Stott, Stone et al. 2004)—shows, this is not an abstract question. Unfortunately, predictions of future climate show not only a change to the base climate, but an increase in both the frequency and severity of such events (Meehl and Tebaldi 2004).

There is no consensus on fundamental definition of what a heat wave is. Definitions vary, from a simple—prolonged period of excessively hot weather—to defining a minimum size and length of excursion (Robinson 2001). In 1900, A. T. Burrows defined a “hot wave” as a spell of three or more days on each of which the maximum temperature reaches or exceeds 90 °F (32.2 °C). Since then many other definitions have been proffered. In the Netherlands, a heat wave is defined as a period of at least 5 consecutive days where the maximum temperature exceeds 25 °C, if on at least 3 of these days the temperature exceeds 30 °C. In Denmark, a heat wave is defined as least 3 consecutive days where the average maximum temperature exceeds 28 °C (DMI 2013). In Sweden, at least 5 days in a row with a daily high exceeding 25 °C is required (SMIH 2013). In the US, definitions vary by region: In the Northeast, a heat wave is defined as three consecutive days where the temperature reaches or exceeds 90 °F (32.2 °C). In Californian, a “heat storm” has occurred when the temperature

reaches 100 °F (37.8 °C) for three or more consecutive days. In South Australia, five consecutive days at or above 35 °C, or three consecutive days at or above 40 °C (104 °F) is required (BOM 2013). A more general measure that compares heat waves in different regions of the World, has been created (Simone, Jana et al. 2015), and this shows areas affected by heat wave occurrences have grown rapidly in the last twenty years (Zampieri, Russo et al. 2016).

In all these cases, the anomaly is defined in terms of external conditions, yet as was shown in Paris in 2003, it is the conditions inside of buildings that lead to excess mortality. There is therefore some logic in considering whether a better definition of a heat wave, or cold snap, would be based on the likely internal conditions of some fraction (say 50%) of buildings. However, this requires knowing the equations that link the response of the stock of buildings to any heat wave of any amplitude or length. This work is an attempt to examine if this might be possible. It should be compared to approaches such as the climate change amplification coefficient which examines the response of buildings to an overall long-term elevation in temperature (Coley and Kershaw 2010).

Building thermal models require a time series of weather variables. When modelling the current situation, a time series constructed from past observed weather is normally used. When modelling the future, either historic weather is morphed (i.e. a mathematical transformation is applied to the historic series) by an amount equal to the predicted change in climate (Jentsch, James et al. 2013), or synthetic future weather is created using a weather generator primed with the expected future climate (Eames, Kershaw et al. 2011). For accurate results to be generated the weather needs to be highly local to the site of the building (Eames, Kershaw et al. 2011).

In part, due to the need for the weather to be local, but also because heat waves and cold snaps are rare by their very nature, it is unlikely that the historic hourly record will contain many, or any such events—particularly any extreme ones that might cause increased mortality. Even if it does contain one, it will be only one of many possibilities with respect to length and amplitude. It will also occur as an excursion from a specific, complex, time series of weather just before the event, and contain unique temporal features during the event (for example the second day of the heat wave might be hotter or colder than the days either side, or the rate of temperature increase each day might be different, or similar). This makes it very difficult to say in a robust way that one heat wave it is equivalent to another mathematically, or with respect to their likely effect on a set of buildings, and probably makes it impossible to create a set of nationally agreed, locally valid, future heat waves of varying sizes and lengths based on complex historic or synthetic time series. Yet, we need some such series if we are to ensure our buildings are robust, and so we can study the scale of the problem in the current stock of buildings.

These confounding factors suggest one possible approach would to create representative heat waves as known simple sinusoidal-like excursions from a known uniform, again sinusoidal-like base signal. A series of these could be created that sequentially represent more extreme heat waves (or cold snaps) and the building tested against these. Predictions of climate change could then be used to associate return periods for the events for each location. We have termed such a time series of weather super synthetic weather. One advantage of such an approach is that there is a range of building thermal models that have analytic solutions to such sinusoidal driving forces when using specific models. For these models the impact of heat waves of all possible lengths and amplitudes lies within analytic solutions themselves.

The question now arises, how would buildings respond to such a time series? Here we take measured energy and temperature data from a set of real buildings, use inverse modelling (Madsen and Holst 1995) to create validated mathematical descriptions of each building, then ask how they

respond to any super-synthetic time series of weather. By using an analytical, rather than a numeric approach, much of the complicating detail is removed, and we are left with an equation that represents the response of the building to changes in external temperature (for example).

METHODOLOGY

In this work, we concentrate on linear models, specifically Lumped Parameter Models (LPMs) based on RC-networks. An RC-network offers a simplified model of the building, which allows systems theory (Ogata 2002) to be applied to analyze their behavior using Bode diagrams or other approaches. As motivation of this work was in part to understand the response of buildings to extreme events, particularly heat waves, the study is performed using data collected during the summer period of May to October. The data collected [1] contains time series of internal temperature, external temperature and electricity use in 25 UK homes cited in Manchester (5 homes) Nottingham (2), Cambridge (5) and Belfast (13) sampled at 5-minutes intervals. The data included internal temperature in three locations of each home from which the mean was calculated.

Solar radiation is a key input for the response of buildings in summer, the MIDAS repository was used in order to obtain this for the four cities during the study period. The global horizontal irradiance was not available directly in the MIDAS database, so the Muneer model was used (Muneer 1990), providing an hourly time series for global horizontal irradiance.

Reduced model. After evaluating a variety of LPMs, it was seen that the best at fitting the internal temperature time series was a second order model with part of the model representing the building envelope and part representing the thermal mass of the building. Similar models have been previously used in the literature with a focus on the response to heating in (Coley and Penman 1992, Fraisse, Viardot et al. 2002, Ménézo, Roux et al. 2002, Xu and Wang 2007, Malisani, Chaplais et al. 2010, Bacher and Madsen 2011). A diagram of the model can be seen in Figure 1. R_1 and R_2 are resistance to the heat flow; C_1 and C_2 are heat accumulators (capacitors); $T_o(t)$ represents the external temperature (taking the form of a source of voltage) and $k_1 g_e(t)$ and $k_2 g_s(t)$ are heat sources (represented as current sources), being the electrical gains and the solar gains respectively. Alternative RC networks either added no more accuracy in internal temperature time series prediction, or the covariance matrices of the parameter estimation had unacceptable values, resulting in unfeasibly large confidence intervals.

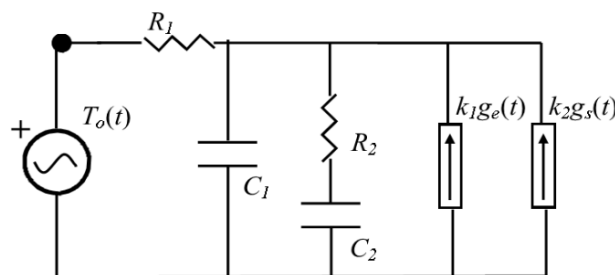


Figure 1. Lumped parameter RC-model used for the work.

Estimation of the models. For the fitting, the system identification toolbox of MATLAB was used, specifically the linear grey-box model estimation routine called greyest. This routine allows the parameters to be found of a linear dynamic model represented as a state-space system. The model had external temperature, electrical gains and solar gains as inputs, and internal temperature as the output to be matched by the grey-box model.

The search method was set to trust method reflective, a search method that uses areas of the

decision space that become smaller as the search progresses. The fit is evaluated by the calculation of the final prediction error (in a least square sense). The bounds of feasible solutions were chosen based on the usual thermal properties of buildings, as found in (CIBSE 2006) and (CLG 2007). The fitting was done by minimization of the final prediction error of the internal temperature. An example of the fitting can be seen in Figure 2; the parameters of the RC-network for each dwelling are given in the appendix.

RESULTS

Having obtained accurate models of the 25 homes, their response to any weather signal can be extracted by looking at the frequency and time response of the RC-networks used to represent the buildings.

Frequency response. The equations of a linear dynamic system can be transformed using Laplace transform from the time domain to the frequency domain. This means that the set of differential equations that govern the system in the temporal domain, become a system of algebraic equations in the frequency domain. In this form, it is possible to know analytically the response of the system to any oscillatory input (in our case external temperature, electrical gains, and solar gains).

For linear systems, any input with an oscillatory nature will produce an output that also has an oscillatory nature, and with the same frequency, but different amplitude and phase (i.e. it will lag against the input). A common way of representing this is with a Bode diagram (Ogata 2002). Bode diagrams provide the gain that the amplitude of an input will have when passed through the system, and the phase change (lag). Bode diagrams are normally represented using decibels. However, temperatures are not commonly presented in decibels, so to facilitate the reading of the results we have decided to plot the simple ratio between the amplitude of the output with respect to the amplitude of the input.

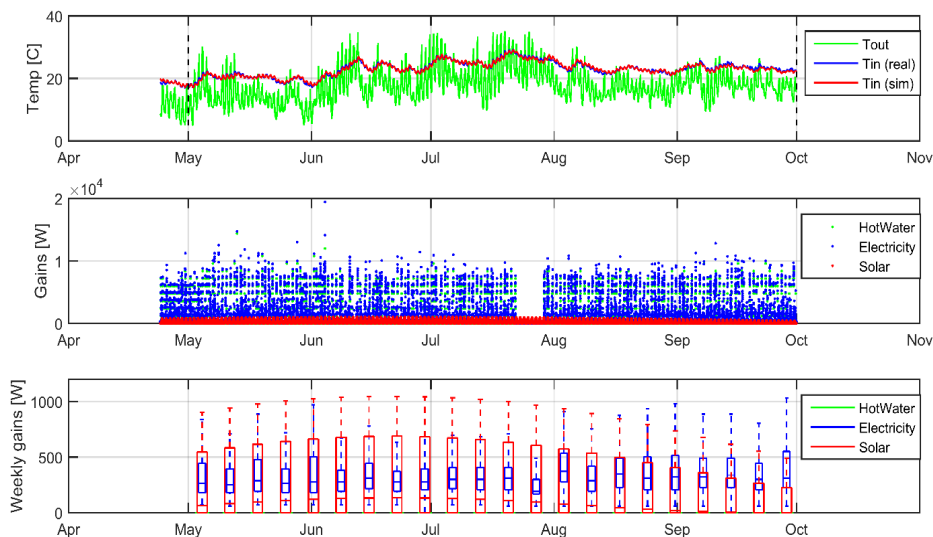


Figure 2. Example of fitting of the LPM model. The fitting of the internal temperature for this dwelling has an R^2 of 85.02%.

In Figure 3a, we see the relationship between inside and outside temperature amplitude depending on the frequency. One can see directly in this graph, that for these dwellings a weekly of,

for example, 10 kelvin (mean-to-peak) will result in an internal temperature oscillation that depends on the dwelling in question, but is typically around 3 degree kelvin (mean-to-peak).

The external temperature is not the only driving force for a building, and we can ask how the system might perform when exposed to, for example, an oscillation in electrical gains. The result, Figure 3b and e, shows as before, the attenuation and lag the building applies to the driving force. The figure shows the small increment in internal temperature that will be seen when an oscillation of one watt of electrical gain is occurs in the house. In contrast to the previous case, the relationship between the driving force and the output is not direct, as the electrical gains are heat and not temperature. It is for this reason that even with large periods the gain diagram does not converge to 1. Instead it converges to the steady-state heat transfer coefficient of each dwelling.

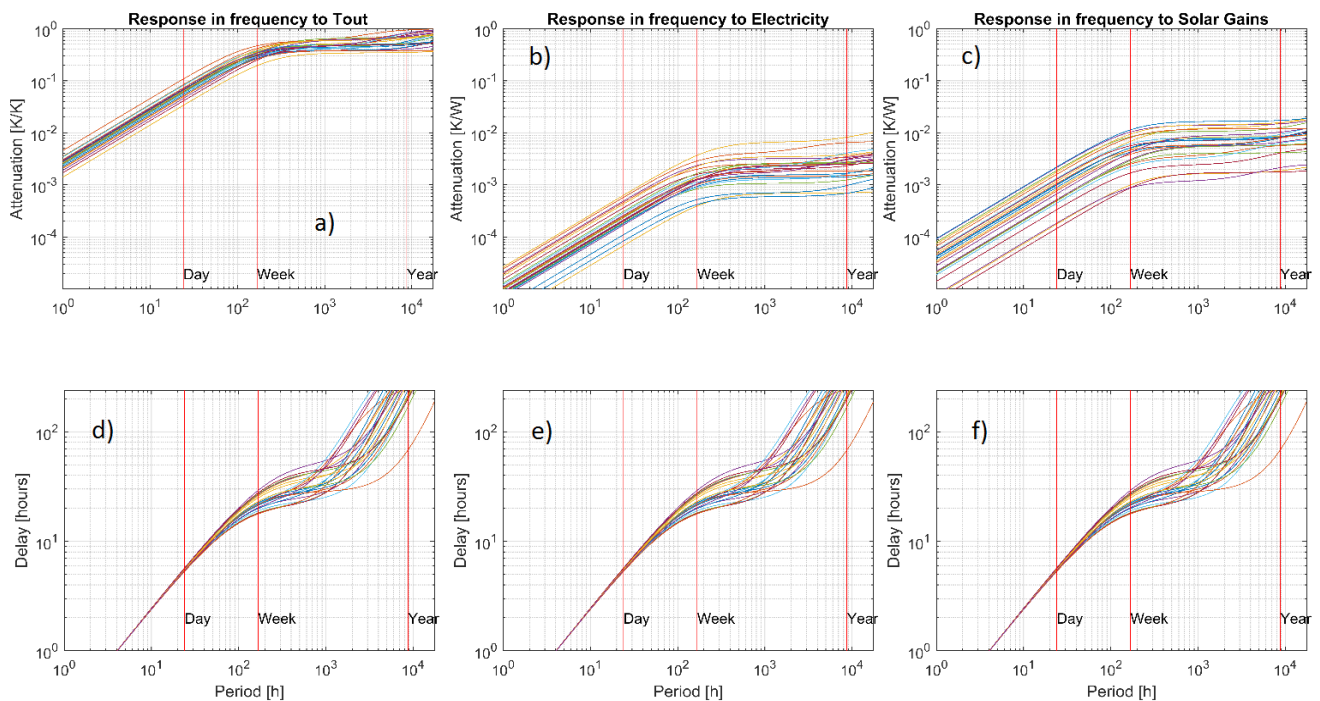


Figure 3. Bode diagrams showing the response of the 25 dwellings to an oscillation in external temperature, electrical gains and solar gains respectively with periods from one hour to a year

The solar gains come also in the form of heat, but not all global horizontal irradiance ends up as heat in all houses. Instead, each one of the dwellings will have an effective window area that will determine roughly how much of any solar horizontal irradiance ends up in the interior of the house and therefore affects the internal temperature, this includes that via windows but also any transmission through opaque elements. It should be noted that the effective area is not an actual area; it is a parameter that provides an estimation of how much energy from the sun reaches the internal spaces. The resultant attenuation and lag of internal temperature due to time varying solar gains is shown in Figure 3c and f.

Time domain demonstration. Switching from the frequency to the time domain allows us to examine analytically for the first time what might happen to a house during a heat wave. As an example, the effect of a super-synthetic heat wave that increments the outside temperature by 5 kelvin during a three -day period (72 hours) was used. This implies that the heat wave is the first half of a sinusoidal of period 144 hours.

Figure 4a, is equivalent to the graph in Figure 3a multiplied by 5, i.e. for an oscillation of 5

kelvin (trough-to-peak), rather than 1 kelvin. These curves therefore give the amplitude of the increments in internal temperature that this heat wave will produce in the dwellings. The increment in internal temperature is shown in Figure 4b. The effect of that heat wave has its maximum effect around the night of the third day, and that the effect of the heat wave will, as expected, vary greatly depending on the construction of the given house. The result is a 0.75 to 2.2 kelvin increase in the temperature of the homes compared with the temperatures of the dwellings before the heatwave. This gives us a simple, but mathematically satisfying, way to compare the risk each dwelling might pose to occupants.

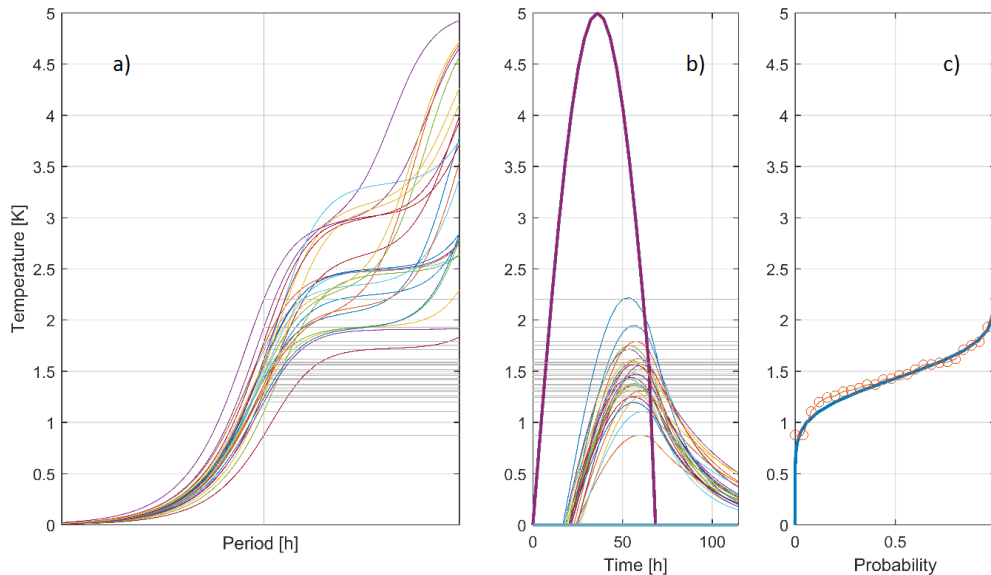


Figure 4. a) Maximum temperature of the increment in temperature in the houses under study under a synthetic heat wave of 5 degrees and 3 days. b) Response in the time domain, the solid blue line is the driving force and the thin colour lines are the responses in each one of the houses. c) Cumulative probability distribution of the maximum increment in temperature in red circles and fitted normal cpf.

If we make the assumptions that (i) these dwellings are reasonably representative of the UK housing stock (which may or may not be true, and which we hope to examine in future work), and (ii) that the range of the results can be characterized by a normal distribution, then we can get an idea of the impact such a heat wave might have on the whole population of homes in the UK, rather than on this sample. The cumulative probability of the resultant normal distribution is shown in Figure 4c. The normal distribution has parameters mean=1.48 and sigma=0.27. This indicates that a heat wave of three days with a maximum amplitude of 5 degrees above the situation prior to the heat wave will result on an increment in internal temperature of 1.5 kelvin or more for 43.3% of the dwellings and a rise of 2 kelvin or more in 3.5% of the dwellings by the third day of the heat wave.

CONCLUSIONS

In this work, we have reduced what is normally considered a numeric problem only amenable to numerical solution via simulation to an analytical one. This was done by taking measured temperature data from 25 homes, then finding simple linear models (equations) that gave the same internal temperature series. Given these equations, we can then ask what the impact would be of a heat wave of any amplitude and of any duration. Using such an analytic approach removes much of the complexity such as the exact form of the weather time series prior and during a heat wave (or cold snap), and (given a large enough sample size) provides a risk analysis of the whole national domestic stock to heat waves of any amplitude or duration.

As expected, the response is building dependent, and no doubt this comes down to questions of

thermal mass, ventilation strategy and levels of insulation. This suggests that the method demonstrated here might form the basis of quantitative guidance on construction strategies that might make buildings more resilient to future heat waves, which do not suffer from criticisms connected to the exact form of the future weather (which is unknown), or the precise details of the buildings (which therefore make any results not pertinent to other buildings), or the exact behavior of occupants (which is poorly understood in the current climate, and unknown in any future climate).

It is worth mentioning that the models were also able to obtain the effective window area of each building with respect to the impact of global horizontal irradiance on internal solar gains. This factor also has large implications on the effect a heat wave may have on a given building.

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APPENDIX

Table A. Parameters of the LPMs

| House | k_1 [W/K] | C_1 [J/K] | k_2 [W/K] | C_2 [J/K] | gS [Wm ² /W] | R^2 |
|-------|-------------|-------------|-------------|-------------|---------------------------|------------|
| 1 | 2.83E+02 | 1.88E+04 | 3.44E+02 | 1.07E+06 | 4.91E+00 | 4.2807e+01 |
| 2 | 1.44E+02 | 6.46E+03 | 9.19E+01 | 3.29E+04 | 8.63E-01 | 6.3152e+01 |
| 3 | 7.75E+01 | 5.93E+03 | 6.76E+01 | 9.98E+04 | 1.84E+00 | 4.9638e+01 |
| 4 | 1.18E+02 | 7.57E+03 | 1.87E+02 | 7.26E+05 | 4.35E+00 | 6.7186e+01 |
| 5 | 4.30E+02 | 1.97E+04 | 4.83E+02 | 9.55E+05 | 9.91E+00 | 7.1415e+01 |
| 6 | 3.30E+02 | 1.52E+04 | 3.33E+02 | 1.64E+06 | 5.40E+00 | 6.1290e+01 |
| 7 | 2.42E+02 | 1.46E+04 | 2.76E+02 | 1.80E+05 | 1.30E+00 | 6.2810e+01 |
| 8 | 5.79E+02 | 3.37E+04 | 8.04E+02 | 9.58E+05 | 8.06E+00 | 6.0943e+01 |
| 9 | 3.33E+02 | 1.85E+04 | 3.33E+02 | 1.64E+06 | 3.76E+00 | 4.4238e+01 |
| 10 | 4.90E+02 | 5.51E+04 | 9.26E+02 | 6.64E+06 | 1.20E+01 | 7.0460e+01 |
| 11 | 2.66E+02 | 1.76E+04 | 1.54E+02 | 2.43E+05 | 2.42E+00 | 5.6592e+01 |
| 12 | 2.48E+02 | 1.60E+04 | 1.23E+02 | 4.35E+05 | 2.09E+00 | 6.2067e+01 |
| 13 | 3.28E+02 | 2.09E+04 | 4.36E+02 | 6.42E+05 | 5.65E+00 | 5.3883e+01 |
| 14 | 1.87E+02 | 1.02E+04 | 2.95E+02 | 6.56E+05 | 3.50E+00 | 6.3083e+01 |
| 15 | 3.58E+02 | 2.04E+04 | 3.55E+02 | 1.51E+06 | 1.20E+01 | 6.6257e+01 |
| 16 | 2.31E+02 | 8.00E+03 | 1.55E+02 | 1.30E+05 | 2.27E+00 | 5.4352e+01 |
| 17 | 2.51E+02 | 1.50E+04 | 1.64E+02 | 3.33E+05 | 7.00E-01 | 8.5024e+01 |
| 18 | 2.67E+02 | 2.22E+04 | 1.60E+02 | 2.91E+05 | 3.93E+00 | 6.2448e+01 |
| 19 | 1.92E+02 | 1.21E+04 | 1.92E+02 | 1.31E+06 | 1.58E+00 | 4.7480e+01 |
| 20 | 1.96E+02 | 1.29E+04 | 2.62E+02 | 1.23E+05 | 1.53E+00 | 4.0694e+01 |
| 21 | 1.98E+02 | 1.83E+04 | 2.03E+02 | 1.25E+06 | 7.00E-01 | 2.3202e+01 |
| 22 | 6.34E+02 | 4.45E+04 | 1.00E+03 | 2.11E+06 | 1.20E+01 | 3.6074e+01 |
| 23 | 2.06E+02 | 1.53E+04 | 3.34E+02 | 1.00E+07 | 6.47E+00 | 6.6752e+01 |
| 24 | 1.69E+02 | 8.73E+03 | 1.10E+02 | 2.86E+05 | 4.09E+00 | 6.0397e+01 |
| 25 | 2.71E+02 | 1.42E+04 | 3.04E+02 | 1.55E+05 | 7.00E-01 | 4.2807e+01 |